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RESEARCH ARTICLE

Social networks and transformative behaviours in a grassland social-ecological system

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Abstract

1. Social connections among individuals are essential components of social-ecological systems (SESs), enabling people to take actions to more effectively adapt or transform in response to widespread social-ecological change. Although scholars have associated social connections and cognitions with adaptive capacity, measuring actors' social networks may further clarify pathways for bolstering resilience-enhancing actions.
2. We asked how social networks and socio-cognitions, as components of adaptive capacity, and SES regime shift severity affect individual landscape management behaviours using a quantitative analysis of ego network survey data from livestock producers and landcover data on regime shift severity (i.e. juniper encroachment) in the North American Great Plains.
3. Producers who experienced severe regime shifts or perceived high risks from such shifts were not more likely to engage in transformative behaviour like prescribed burning. Instead, we found that social network characteristics explained significant variance in transformative behaviours.
4. *Policy implications*: Our results indicate that social networks enable behaviours that have the potential to transform SESs, suggesting possible leverage points for enabling capacity and coordination toward sustainability. Particularly where private lands dominate and cultural practices condition regime shifts, clarifying how social connections promote resilience may provide much needed insight to bolster adaptive capacities in the face of global change.

KEYWORDS
adaptive capacity, collective action, livestock producer, prescribed burning, regime shift, social network analysis, transformation, woody encroachment

1 | INTRODUCTION

Regime shifts are occurring more frequently in large social-ecological systems (SESs), threatening to collapse ecosystems and biomes across the globe (Bestelmeyer et al., 2015; deYoung et al., 2008; Gilarranz et al., 2022; Gunderson et al., 2017). Regime shifts occur when a system switches from one regime to another persistent regime (Walker et al., 2004) and can be navigated, resisted, or directed through adaptive capacity (Lynch et al., 2022). Although it is generally appreciated that social networks play a role in mobilising adaptive capacity, greater attention to the mechanisms operating through social networks is needed to achieve conservation objectives at scale (Bodin et al., 2019). Ego network approaches are an underexplored way to study individuals' immediate contacts, providing an opportunity to study social networks and draw inference at a scale that matches the extent of social-ecological change.

Adaptive capacity—the latent ability to respond to or manifest change—contributes to resilience, such that an SES retains the 'same function, structure, feedbacks, and therefore identity' (Walker et al., 2004) through adaptation, and transformative capacity enables a transition into a different regime through transformation (Chaffin et al., 2016). While there is little consensus on the distinction between adaptive and transformative capacities, it is likely that different dimensions are important for adaptation versus transformation (Garmestani et al., 2019). For consistency with the literature (Cinner & Barnes, 2019), we use 'adaptive capacity' to refer to adaptive and transformative capacities throughout the remainder of the paper. Adaptive behaviours enhance system resilience to maintain the current regime, whereas transformative behaviours deliberately change the nature of the system (Chaffin et al., 2016). SESs are comprised of social and ecological components linked through complex feedbacks across nested scales to generate emergent properties (Colding & Barthel, 2019). Different dimensions of adaptive capacity interact across scales to promote adaptation and transformation (Cinner & Barnes, 2019). These dimensions can include *agency*, which is both the power and ability of individuals to act; *assets* to which people have access, including economic, infrastructure, and health services; *flexibility* and diversity of adaptation options; *learning* new information; *social organisation*, which can enhance trust, cooperation, and collective actions; and *socio-cognitions* like beliefs, risk attitudes and perceived social norms (Cinner & Barnes, 2019). Although there has been considerable conceptual development of adaptive capacity over the last few decades (Vallury et al., 2022), the role of social organisation—especially social networks—remains underexplored (Bodin et al., 2019).

With this study, we capitalise on how social network approaches can provide a mechanistic understanding of social factors influencing behaviour (Bodin & Prell, 2011). This perspective suggests several mechanisms by which social networks influence individuals' behaviours: access to information, exposure to social influence, and availability of social support. We focus on how producers' information access and availability of social support through their social connections affects individuals' land management behaviours that then aggregate, or scale up, to larger collectives to determine adaptation or transformation in nested SESs, a central question for global sustainability. By quantifying the extent to which network-provided information access and social support affect individual behaviour, our approach can reveal tangible avenues for encouraging adaptive or transformative actions to manage the environment. For example, information access is enhanced by heterogeneous networks, characterised by ties between dissimilar people or groups who bring different points of view and experiences. Network heterogeneity has been shown to enable the spread of novel information (Granovetter, 1973; Hahn et al., 2006), mobilising resources (Sandström & Carlsson, 2008) and improving adaptive capacity (André et al., 2017). Furthermore, collective action may be enabled when groups are sufficiently diversified to accomplish goals that require unique tasks (Hahn et al., 2006; Lubell et al., 2013; Sandström & Carlsson, 2008).

In other instances, individuals with networks composed of contacts who are like them (i.e. homophilous networks) may benefit from mutual understanding and being able to draw on greater social support to embrace adaptive and transformative behaviours that mitigate environmental change (Barnes et al., 2020; Coleman, 1988; Teodoro & Prell, 2023). Dense connections among actors may ease knowledge transfer through increased interaction (Reagans & McEvily, 2003) that increases adaptive behaviour and collective action (Isaac et al., 2007; King, 2000) or reduce adaptive responses due to social homogenisation and constraint (Bodin & Norberg, 2005; Burt, 2004). Various socio-cognitive factors drive collective action, including social pressure, trust and perceptions of group efficacy and risk, each of which are affected through social networks (Bodin & Crona, 2009; Lubeck et al., 2019; Lubell et al., 2013; Niemiec et al., 2016).

Two broad approaches to studying social networks include whole network and ego network designs (Figure 1) (Borgatti et al., 2013; Crossley et al., 2015). Whole network studies, in which researchers analyse relationships, or ties, between members of a predefined group, are common in SES literature (Bodin & Prell, 2011; Crona & Bodin, 2010) and are appropriate for studying how relationship patterns within a group relate to individual or collective outcomes. Less common are ego network studies, in which researchers sample individuals to understand the importance of interpersonal relationships to individual cognitions and behaviours (e.g. Tindall & Robinson, 2017). The person of focus is referred to as "ego," while ego's contacts are referred to as "alters." In ego network studies, researchers ask individuals to identify each of their alters, describe their ties with these alters, and describe the ties among their alters. This approach is useful when research questions focus on the immediate social environment within which an ego is situated; the unit of analysis is the individual and all relationship data collected are from the perspective of the individual. Because ego network researchers sample from the population, each ego's alters need not be an ego in the study and standard statistical procedures can be used to make inferences to the general population. Thus, ego network studies provide an opportunity to examine social network influences at

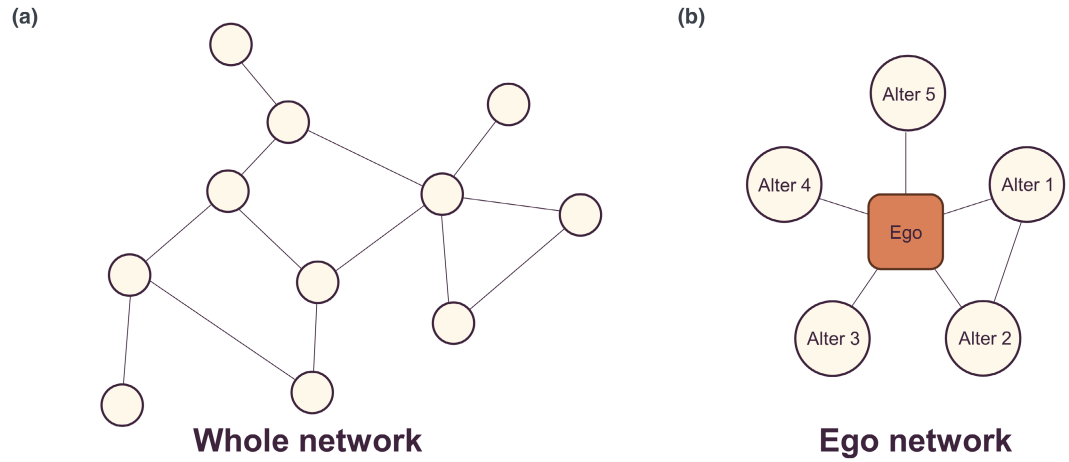

FIGURE 1 Network diagrams showing people (nodes) connected by relationships (ties) for (a) a whole network and (b) an ego network.

the same scale as larger-scale ecological processes. In addition to sampling and statistical inference benefits, ego network approaches allow researchers to study the effects of "intersecting social circles," rather than one predefined group, on ego outcomes (Crossley et al., 2015; Simmel, 1955). This benefit is particularly important in cases where researchers expect that multiple social domains influence an individual's behaviour, as is likely the case for many private land managers, who interact with family, community members, government representatives and others to manage their operation.

Human behaviour can be affected by social as well as ecological processes, but social processes may be more effective at inspiring adaptive or transformative behaviours to manage the environment. Although scholars have long recognised that resilience is jointly social and ecological (Adger et al., 2000), few have investigated the relative effects of social processes on behaviour as compared to ecological processes, though the hazard literature is a notable exception (Norris et al., 2008; Wickes et al., 2015). There are numerous opportunities for those seeking to understand how human behaviour changes proactively, before ecological change materialises. For example, understanding how social organisation and sociocognitive dimensions of adaptive capacity affect behaviours may be particularly instructive for limiting the pace and extent of undesirable SES regime shifts.

1.1 | The SES

The North American Great Plains is a temperate grassland biome experiencing widespread shifts from grassland to woody-dominated regimes, in which individual adaptive capacity is being mobilised toward adaptive and transformative behaviour (Figure 2a). Prior to European settlement, the North American Great Plains biome (hereafter "Great Plains") was characterised by extensive grasslands maintained through feedbacks among fire, humans, herbivores and climate (Engle et al., 2008; Rossum & Lavin, 2000). The Great Plains provides critical habitat for numerous at-risk species, including grassland obligate species like the lesser prairie chicken (*Tympanuchus pallidicinctus*) (Chapman et al., 2004). The Great Plains is also home to a significant proportion of US cattle operations, producing approximately 50% of American beef (Wishart, 2004), a $73 billion dollar industry (USDA Economic Research Service, 2022). After more than 5000 years of grassland domination (Nordt et al., 2008), woody plants such as Ashe juniper (*Juniperus ashei*) and Eastern redcedar (*J. virginiana*) are spreading at unprecedented rates (Briggs et al., 2005). This process, referred to as woody encroachment, is largely the outcome of fire exclusion and large-scale tree planting programs in the Great Plains (Taylor et al., 2012). Transitions from grassland to woody-dominance can reduce livestock forage productivity (Fuhlendorf et al., 2008), displace prairie chickens (Lautenbach et al., 2017), reduce streamflow and groundwater recharge (Zou et al., 2018) and intensify wildfires, when they do occur (Donovan et al., 2020).

Agricultural producers are individually and collectively responding to the threat of this regime shift on their operations using mechanical tree removal and prescribed burning depending on the stage of encroachment (Figure 2b,c). Prescribed burning, a practice common in Indigenous cultures, is having a resurgence as the Eurocentric paradigm of fire exclusion begins to shift in recognition of the essential role disturbance plays for the resilience of SESs, including grasslands (Twidwell et al., 2013; Weir et al., 2016). Prescribed burning involves managing fire across a landscape with people who have diverse skillsets and resources necessary to acquire fire permits or control fire boundaries through coordinated collective action (Twidwell et al., 2013; Weir et al., 2016). Prescribed burning is not widely used because it challenges pervasive social paradigms to exclude fire despite its potential to manage the regime shift effectively at scale. Because it changes fundamental systemic relationships, feedbacks and processes, returning prescribed burning to the landscape at large spatial scales has the potential to be truly transformative for this fire-dependent SES (Garmestani et al., 2020). In contrast, mechanical removal is a socially acceptable adaptation that is frequently used, but is insufficient to address the scale of the regime shift, primarily because of implementation costs. In Nebraska, at the heart of the Great Plains, there is an evolving social response to this

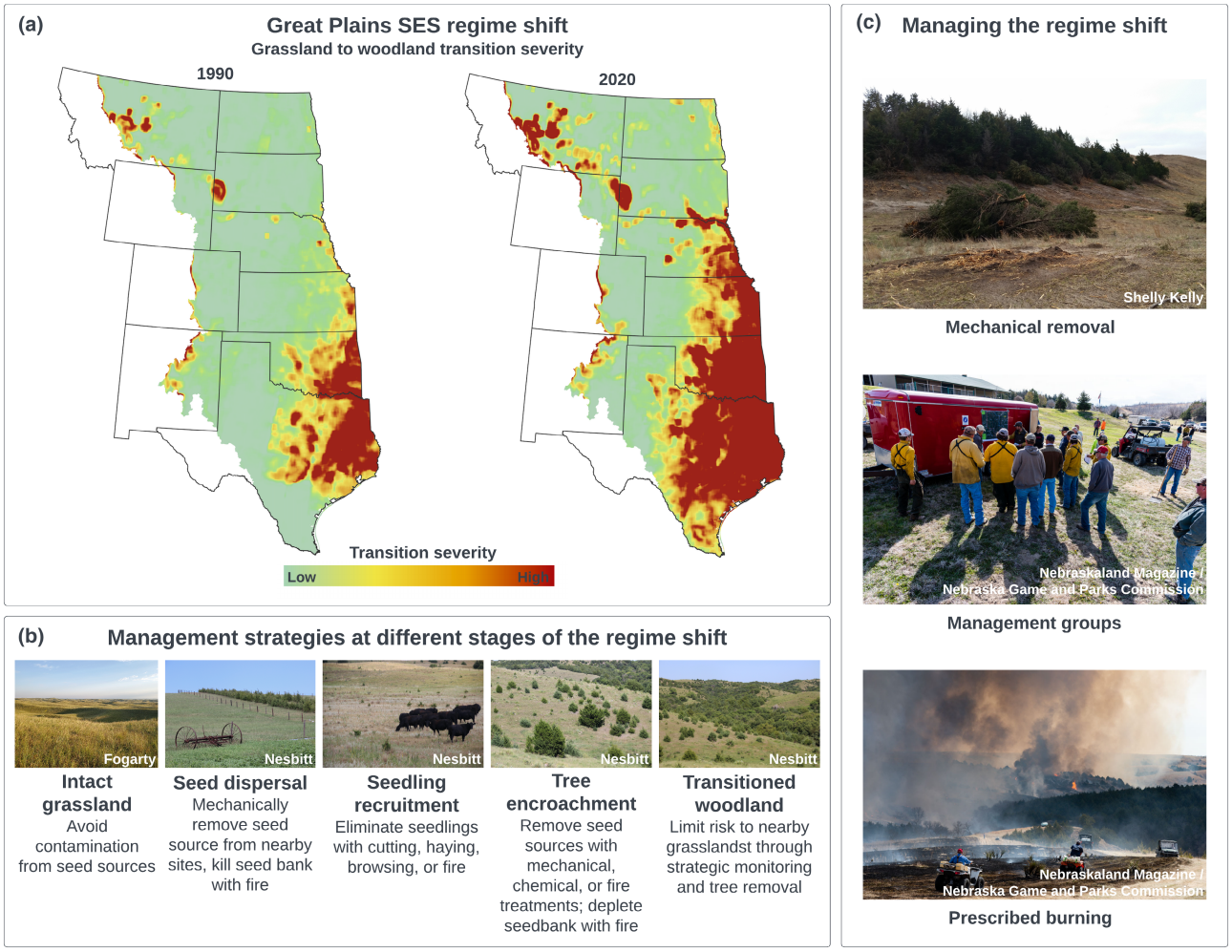

FIGURE 2 Widespread shifts from grassland to woody-dominated regimes in the Great Plains constitute an SES regime shift. (a) Grassland to woodland transition severity from 1990 to 2020 (Twidwell et al., 2021; Uden et al., 2019). (b) Management strategies at different stages of the regime shift. (c) Land managers at work. SES, social-ecological system.

regime shift including individual actions, informal partnerships, and institutionalised networks (Twidwell et al., 2013; Weir et al., 2016).

1.2 | Theoretical framing and hypotheses

We investigated how individuals' social networks, socio-cognitions and SES regime shifts related to adaptive and transformative behaviours of livestock producers in Nebraska. To do so, we administered an ego network survey in 2021, leveraged landcover data, and built logistic regressions predicting each behaviour to test our hypotheses.

The conceptual model shown in Figure 3 illustrates how social relational factors of adaptive capacity and ecological change influence the uptake of adaptive and transformative behaviours. We used the adaptive capacity framework developed by Cinner and Barnes (2019) because it explicitly calls attention to the role of social relational factors (i.e. socio-cognitions and social organisation) influencing an individual's ability to adapt or transform. Because adaptive capacity is a latent construct, mobilised into human behaviour by stress, clarifying the degree to which social factors activate human behaviour relative to ecological factors may reveal ways in which actions can be initiated proactively, that is prior to transitions, through social means. Thus, to understand the relative importance of ecological change compared to social relational factors, we included an SES regime shift factor in our conceptual model. We compared adaptive and transformative behaviours in our conceptual model because we suspected that different factors influence their uptake, and their level of importance for scaling up a sustainable management response to SES regime shifts varies.

We begin with three hypotheses predicting the relative influence on transformative and adaptive behaviours of the existence of social networks, regime shifts, and socio-cognitive factors.

> **Hypothesis 1.** Social networks will be more predictive of transformative behaviour (i.e. prescribed burning) than regime shifts because of the access to information or social support required to enable

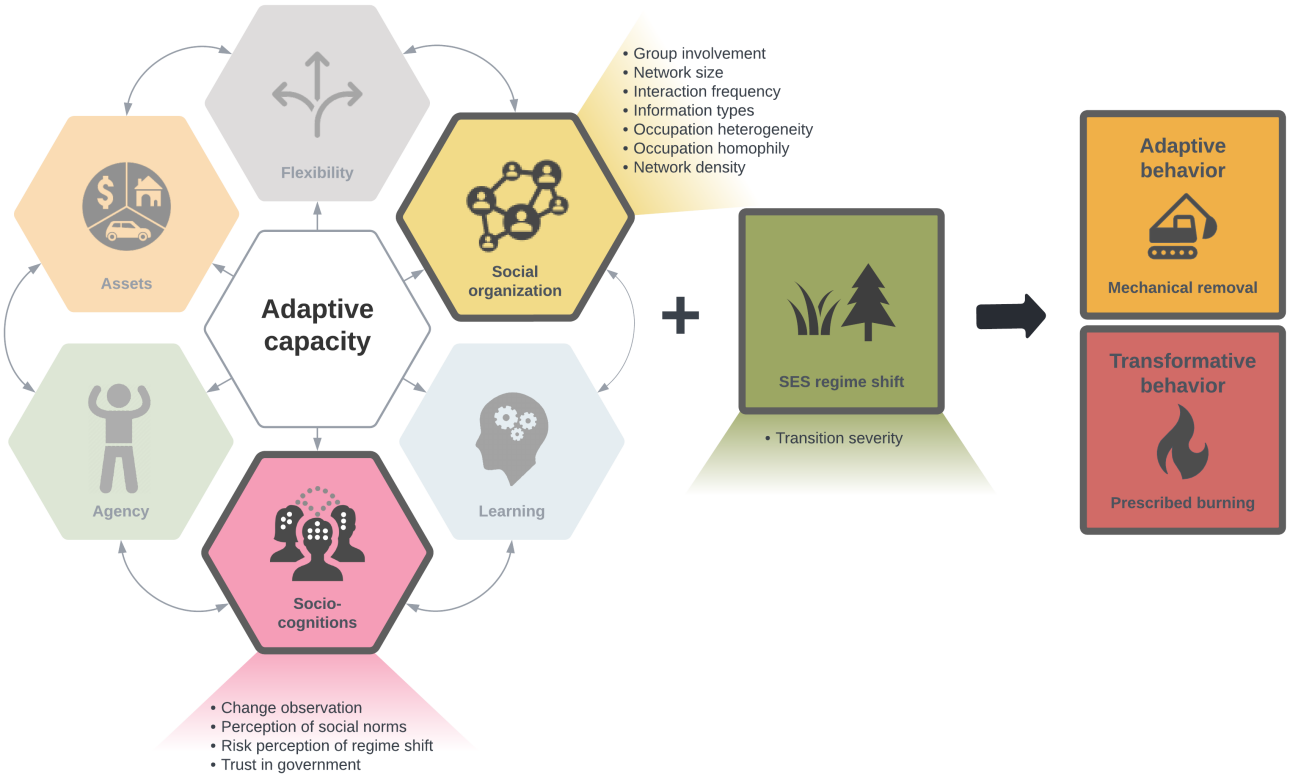

FIGURE 3 Conceptual model of the social organization and socio-cognitive dimensions of adaptive capacity that may be mobilized amidst a social-ecological system (SES) regime shift to affect individual behaviours. Variables used to quantify each of these dimensions are listed in bullets. The adaptive capacity portion of this figure was modified from Cinner and Barnes (2019).

collective actions that challenge underlying fire exclusion paradigms.

Hypothesis 2. Regime shifts will be more predictive of adaptive behaviour (i.e. mechanical removal) than social networks because socially acceptable actions that individuals can undertake alone require little collective support, but by definition require the presence of the catalyst (junipers).

Hypothesis 3. Socio-cognitions will be predictive of both adaptive and transformative behaviours because trust and perceptions of risk, environmental change, and normative pressure typically influence land management decisions.

Further, we explore how social network characteristics, regime shifts and socio-cognitions differentially influence behaviour.

1.3 | Social networks and management behaviours

Regarding social network characteristics, we argue that individuals with large, heterogenous networks may have access to the information and resources required to engage in adaptive and transformative behaviours. For example, individuals with large ego networks may have access to novel information and more resources (Waters & Adger, 2017), such that larger ego networks have been associated with conservation oriented behaviour (Lubell & Fulton, 2008). Similarly, individuals with heterogenous ego networks may perceive both higher environmental risks and higher individual adaptive capacity (André et al., 2017). Thus, we predicted producers with large, heterogeneous ego networks who received different types of information from their contacts would be more likely to engage in prescribed burning because they have access to information and resources enabling them to challenge pervasive fire exclusion paradigms. We did not expect these variables to predict mechanical removal of trees, which does not have the same stigma and risks as prescribed burning.

Hypothesis 4. Producers with (1) large and (2) heterogeneous networks will be more likely to engage in prescribed burning.

Alternatively, because coordinated group efforts are needed to safely conduct prescribed burning, this transformative behaviour may be more effectively enabled in close knit communities. Research on networks and social support suggests whole networks characterised by strong ties and similarity may be more likely to engage in collective action due to trust and expectations of reciprocity (Bodin & Crona, 2008; Coleman, 1988; Granovetter, 1985; McPherson et al., 2001; Newig et al., 2010). Organisational research on ego networks suggests that social knowledge is transferred through

close ties (Uzzi & Lancaster, 2003) and those with social knowledge are better able to implement innovations (Obstfeld, 2005). Environmental governance research on whole networks suggests that joint action is more likely among geographically proximate managers with interdependent risk and relationships characterised by trust (Bodin et al., 2020; Hamilton et al., 2019). Thus, we predicted producers with networks characterised predominantly by other producers (i.e. high occupation homophily) and strong ties with their contacts, measured as interaction frequency in our study, would be more likely to use prescribed burning because of the social support they receive from their neighbours. Because mechanically removing trees does not require collective action, we did not expect these variables to be related to mechanical removal.

> **Hypothesis 5.** Producers with networks characterized by (1) occupational homophily and (2) strong ties will be more likely to engage in prescribed burning.

While dense connections among actors can facilitate information exchange in whole networks (Reagans & McEvily, 2003), the benefits of high network density may plateau by limiting access to novel information and constraining behaviour of individuals (Burt, 2004). Indeed, several studies on organisations suggest a negative quadratic relationship between density and information exchange (Hansen, 1999; Oh et al., 2004; Uzzi, 1999). In the environmental governance literature, empirical work has shown that adaptive behaviour declines with increasing ego network density (Isaac & Dawoe, 2011). Additionally, whole network simulations suggest that resilience and network performance decline at high densities because high amounts of information exchanged among dense connections homogenises responses to environmental variation and limits adaptive capacity (Bodin & Norberg, 2005; Little & McDonald, 2007). We expected a negative quadratic relationship between density and behaviour, predicting that prescribed burning would be highest at moderate densities because network structure provides a 'sweet spot' of novel information and social support. We did not expect a relationship between density and mechanical removal because novel information and social support is less important for behaviours that are commonly implemented.

> **Hypothesis 6.** Producers with networks characterized by moderate levels of density will be more likely to engage in prescribed burning.

1.4 | Regime shift observations, transition severity and management behaviours

Regarding the influence of regime shifts, we predicted that observing woody encroachment (i.e. change observation) would increase behaviours to manage it, much like the positive effects of risk salience on adaptation in farmers (Azadi et al., 2019) and the value of engaging in weed control behaviours in landholders (Lubeck et al., 2019). Because adaptive capacity is by definition a latent ability to adapt, it may be mobilised into behaviour by regime shifts. We expected that transition severity would have a positive relationship with both management behaviours.

> **Hypothesis 7.** Producers who observe woody encroachment will be more likely to engage in behaviours aimed at managing it.

> **Hypothesis 8.** Increasing transition severity will increase the likelihood that producers will engage in prescribed burning and mechanical removal.

1.5 | Norms, risk, trust and management behaviours

Social norms have been shown to affect behaviours to control weeds (Lubeck et al., 2019) and invasive trees (Niemiec et al., 2016). Thus, we predicted that those who perceived social norms around preventing woody encroachment would be more likely to engage in preventative behaviours themselves. Risk perception has been shown to positively affect adaptive behaviour, including in farmers adapting to climate change (Azadi et al., 2019) and residents managing invasive trees (Niemiec et al., 2016). Thus, we predicted that those who perceived high risks of regime shifts to rangeland profitability, ecosystems, and productivity would be more likely to manage for these transitions. Trust in the information that the government provides and government involvement in conservation has been shown to positively affect adaptive and conservation oriented behaviours (Azadi et al., 2019; Lubell et al., 2013), thus we predicted that increased trust in government would be associated with adaptive and transformative behaviours to manage the regime shift

> **Hypothesis 9.** Producers who perceive social norms encouraging prevention of woody encroachment will be more likely to engage in prescribed burning and mechanical removal.

> **Hypothesis 10.** Producers who perceive greater risk from woody encroachment will be more likely to engage in prescribed burning and mechanical removal.

> **Hypothesis 11.** Producers with greater trust in government will be more likely to engage in prescribed burning and mechanical removal.

2 | MATERIALS AND METHODS

2.1 | Study area

We conducted our research in Nebraska, USA (Figure 4), located within the central Great Plains temperate grassland biome. Here, dominant grassland communities consist of shortgrass, mixedgrass, and tallgrass prairie from west to east following a gradient of decreasing

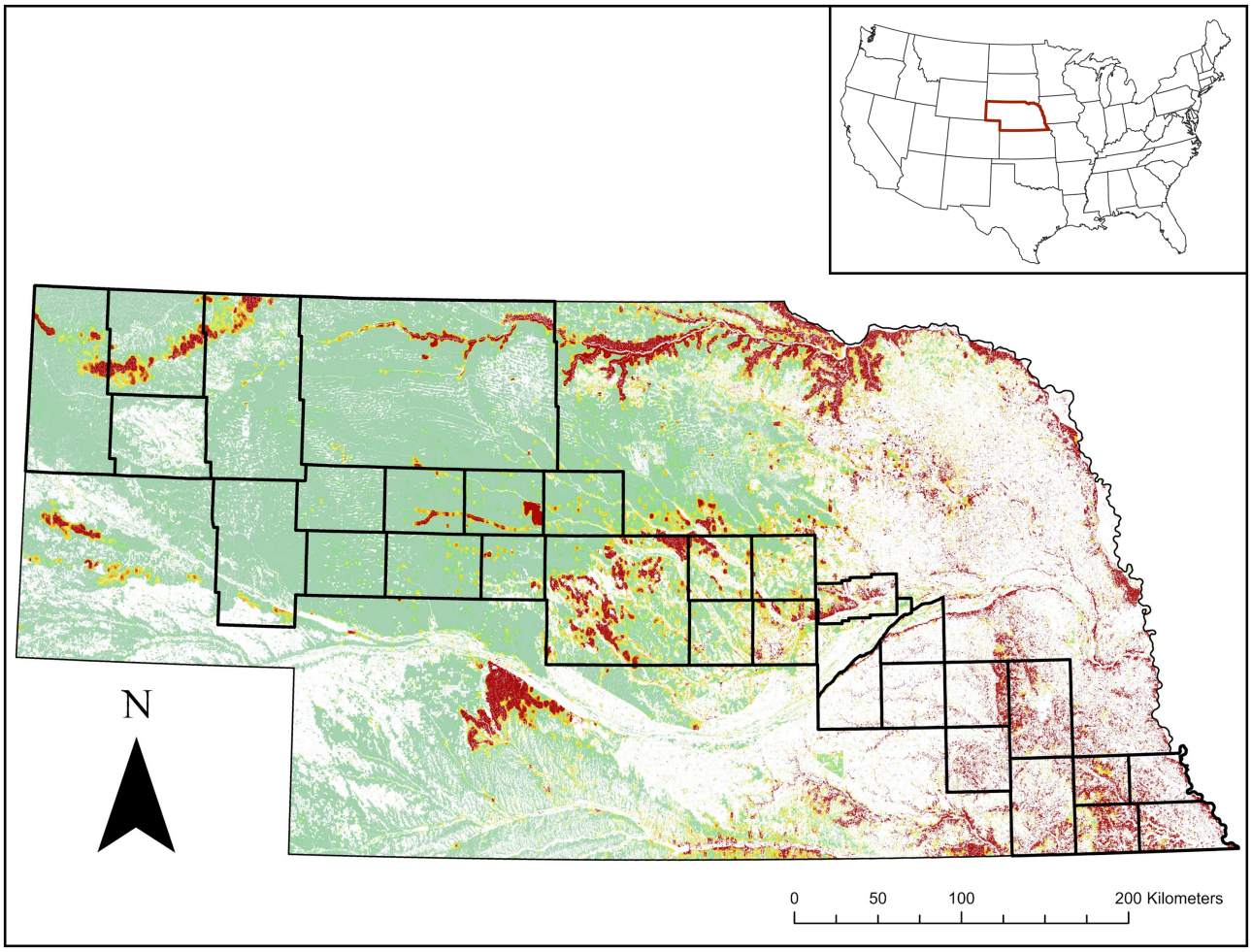

FIGURE 4 Map of Nebraska showing spatial covariance in 2020 in colour. Counties that were sampled are shown and represent a gradient of transition severity between grasslands and woody-dominated regimes.

mean annual precipitation. Cow-calf production on perennial rangelands is the primary land use in the central and western portions of the state, while cropland agriculture is more common in the eastern portion of Nebraska (Chapman et al., 2001). Woody encroachment threatens grasslands across the state to some degree, however, the severity of encroachment tends to increase along an east to west gradient (Natural Resources Conservation Service, 2021).

2.2 | Data collection

2.2.1 | Social data

We used a mail-back and online questionnaire to Nebraska livestock producers in 2021 to collect these data (Supporting Information). Informed consent was acquired (ethics approval: UNL IRB# 20086, UM IRB #235-19). We focused on 31 counties across a northwest to southeast cross-section of Nebraska, which captured a vegetation gradient from grassland (northwest) to woody dominance (southeast; Figure 4). We bought names and addresses from Farm Market iD, a vendor who provides producer data for marketing. The purchased list constitutes the entire population of people who responded to the National Agricultural Statistics Service's survey in the counties we requested and who self-identified as having >20 acres of pasture/rangeland (6546 people) from which we took a simple random sample of 4500. After we removed duplicates, the initial sample size was 4494. We administered the survey using a modified tailored design (Dillman et al., 2014) in May–July 2021. The survey included questions about producers' behaviours, dimensions of adaptive capacity, demographics, and ego networks.

2.2.2 | Ecological data

We calculated transition severity using vegetation classes in the Rangeland Analysis Platform v2.0 (USDA NRCS et al., 2019) based on remotely sensed data from 2020.

2.3 | Measures

We focused on the social relational aspects of adaptive capacity (i.e. social organisation and socio-cognitions; Cinner & Barnes, 2019) and

transition severity as a measure of regime shifts. We included other dimensions of adaptive capacity as covariates.

2.3.1 | Behaviours

We asked respondents how often they had used mechanical removal and prescribed burning to manage vegetation transitions on their operation in the last 3 years and dichotomised their responses from a four-point ordinal scale.

2.3.2 | Social organisation

We quantified social organisation measures for each respondent based on survey responses and characteristics of their ego network. We asked each respondent their level of involvement in local rangeland management groups (Marshall et al., 2016) and predicted that those more involved in such groups would be more likely to manage woody encroachment.

We designed the ego network questions following methods in Burt (1992). We used a name generator prompt (Crossley et al., 2015) asking each respondent (i.e. ego) to list up to 15 contacts (i.e. alters) with whom they work, communicate and seek management advice. We then asked questions about their alters' occupations, how frequently the respondent interacts with each alter, the kinds of information the respondent gets from each alter, and whether the respondent's alters know each other. Based on these questions, we measured the size of each respondent's network (i.e. number of alters), average frequency of interaction with their alters, average number of information types received from their alters, and the density of ties among alters. We also measured occupation diversity among respondents' alters (i.e. occupation heterogeneity) and the extent to which the respondents held the same occupations as their alters (i.e. occupation homophily; Figure 5). See the Supporting Information for more details on these measures.

2.3.3 | Socio-cognitions

We measured each respondent's perceptions of environmental change, social norms, and risk, and trust in the government to manage the regime shift using a 5-point Likert scale (strongly disagree to strongly agree) (Supporting Information).

2.3.4 | Transition severity

We used the spatial covariance (continuous scale) to determine the severity of spatial boundaries between two vegetation classes (perennial forbs/grasses and trees remotely sensed in 2020; Uden et al., 2019). For each respondent's section (~259 ha, per the Public Land Survey System), we averaged the spatial covariance across all pixels, with cropland, water, and developed pixels excluded. Spatial covariance of 0 indicates there are no trees in a grassland regime or there are no grasses in a forest regime. More negative spatial covariance values indicate a greater intensity of spatial transition between forbs/grasses and trees (i.e. stronger/more boundaries), thus we multiplied spatial covariance by −1 for a more intuitive transition severity value.

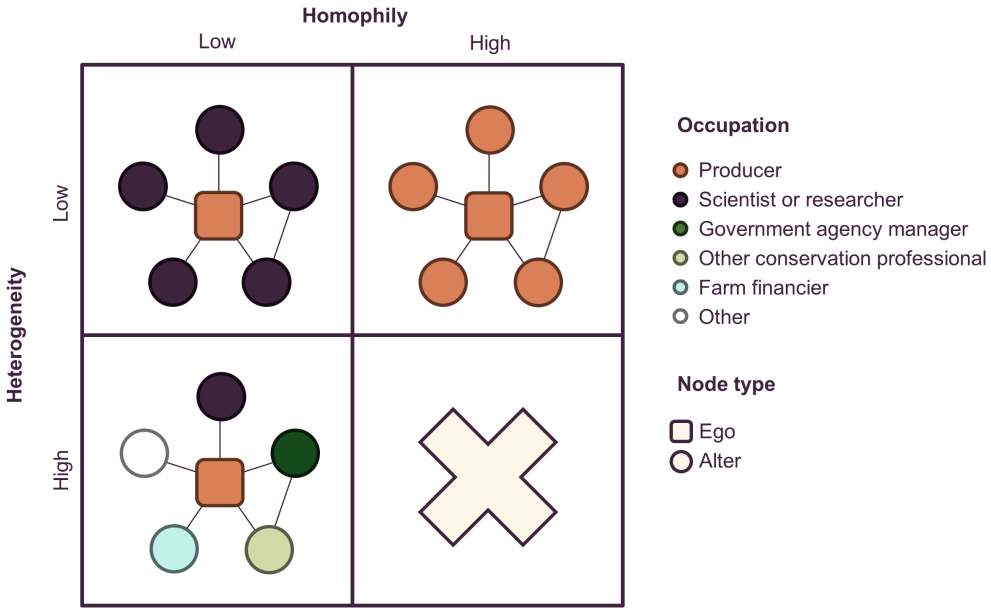

FIGURE 5 Homophily and heterogeneity measure different concepts. Homophily measures ego-alter similarity whereas heterogeneity measures diversity among alters for a given attribute. In our study, we examined occupation homophily and heterogeneity. Node shape indicates the focal person (ego = square, alter = circle) and colour indicates the person's occupation.

2.3.5 | Adaptive capacity covariates

We treated agency, assets, flexibility, and learning dimensions of adaptive capacity as covariates in our model (Supporting Information). Agency, or the ability to act, was measured with the concepts of self- and group efficacy with Likert scales (Lubeck et al., 2019; Niemiec et al., 2016). To measure assets, we asked respondents how many acres they owned or rented for their operation (Lubell et al., 2013). We measured a respondent's flexibility based on their level of education (dichotomised from a 6-point ordinal scale) and income diversity (0–100 scale; Lubell et al., 2013; Marshall et al., 2016). We measured learning through a respondent's years of experience (continuous scale) and their level of innovation and experimentation in agriculture (Likert scale; Marshall et al., 2016).

2.4 | Analysis

We performed factor analysis to reduce the number of variables in the analysis (Supporting Information). We used exploratory factor analysis to generate the efficacy and learning variables, and confirmatory to generate the norms and risk perception variables finding minimum residuals through ordinary least squares with a varimax rotation (psych package; Revelle, 2019) in R (version 3.6.1; R Core Team, 2019). For composite variables, we measured scale reliability with Cronbach's alpha, using a cut-off of 0.6 (Vaske, 2008). To generate composite variables, we took the average of responses. We removed all respondents with incomplete data after generating composite variables.

We built logistic regression models to test the effects of social organisation, socio-cognitions and regime shifts on each behaviour, holding other dimensions of adaptive capacity constant, and built one model for each behaviour. All variables except the behaviours and education were treated as continuous and standardised. We fit global models with all of the explanatory variables in Table S1. We performed backward, forward and iterative model selection, measuring model fit with Akaike's Information Criterion (MASS package; Venables & Ripley, 2002) to come up with a candidate set of models for each behaviour; however, each procedure resulted in the same model (i.e. the "final model") for each behaviour. We examined model diagnostics to check assumptions and model fit (Supporting Information). We used McFadden's pseudo-R^2 (pscl package; Jackman, 2017) to approximate explained variation in our logistic regressions and report model accuracy with cross-validation (60% of the data in the training set, 40% of the data in the testing set).

3 | RESULTS

3.1 | Overview of sample

We received 191 complete responses for this analysis, from a total response rate of 12.8% ($n = 573$) after removing incomplete responses to the ego network portion of the instrument. Our respondent profile (Supporting Information) had a slightly higher income than the average Nebraskan farmer, slightly higher education level than that of the state (Western Economics Services, 2021), and a larger farm size than the state average (USDA NASS, 2021), which we would expect for ranchers, our focal group, compared to other classes of agricultural producers. Operations in the top 99 percentile for planted acres, gross farm income (GFI), and acres in corn production are not represented in our data (i.e. planted acres >5000; GFI >$2.5 million; or >2500 acres in corn production). However, model diagnostics and fit (Supporting Information) indicate these data are appropriate for answering our research questions about the relationships between rancher behaviour, social networks, socio-cognitions, and regime shifts. The majority of respondents used mechanical removal (76%) but not prescribed burning (30%) to manage the regime shift.

3.2 | Model results

All final models significantly predicted behaviours and had little to no evidence of lack of fit (Table S2). Final models performed better than their global and null counterparts (Table 1). McFadden's pseudo-R^2 was 0.16 to 0.29 and prediction accuracy using cross-validation was 62% and 68%, for mechanical and prescribed burning models respectively (Table 1).

3.2.1 | Hypothesis 1—Social networks will be more predictive of transformative behaviour than regime shifts

We found evidence to support our first hypothesis that social networks would be more predictive of transformative behaviour than regime shifts (Figure 6; Table S3). In particular, social network variables—involvement in rangeland management groups (i.e. group involvement; log odds = 0.5, CI = [0.17, 0.84]) and similarity with contacts' occupations (i.e. occupation homophily; log odds = 0.49, CI = [0.07, 0.96])—were significantly ($p < 0.05$) and positively related to prescribed burning. Furthermore, access to different sources of information (i.e. information

TABLE 1 Model information.

	Mechanical removal	Prescribed burning
n	191	191
df	183	183
AIC (global)	183.32	231.97
AIC (final)	163.5	212.54
AIC (null)	210.56	234.84
McFadden's pseudo-R^2	0.29	0.16
Prediction accuracy with cross-validation (%)	68	62

Note: *n* = sample size.

Abbreviations: AIC, Akaike's information criterion; df, degrees of freedom.

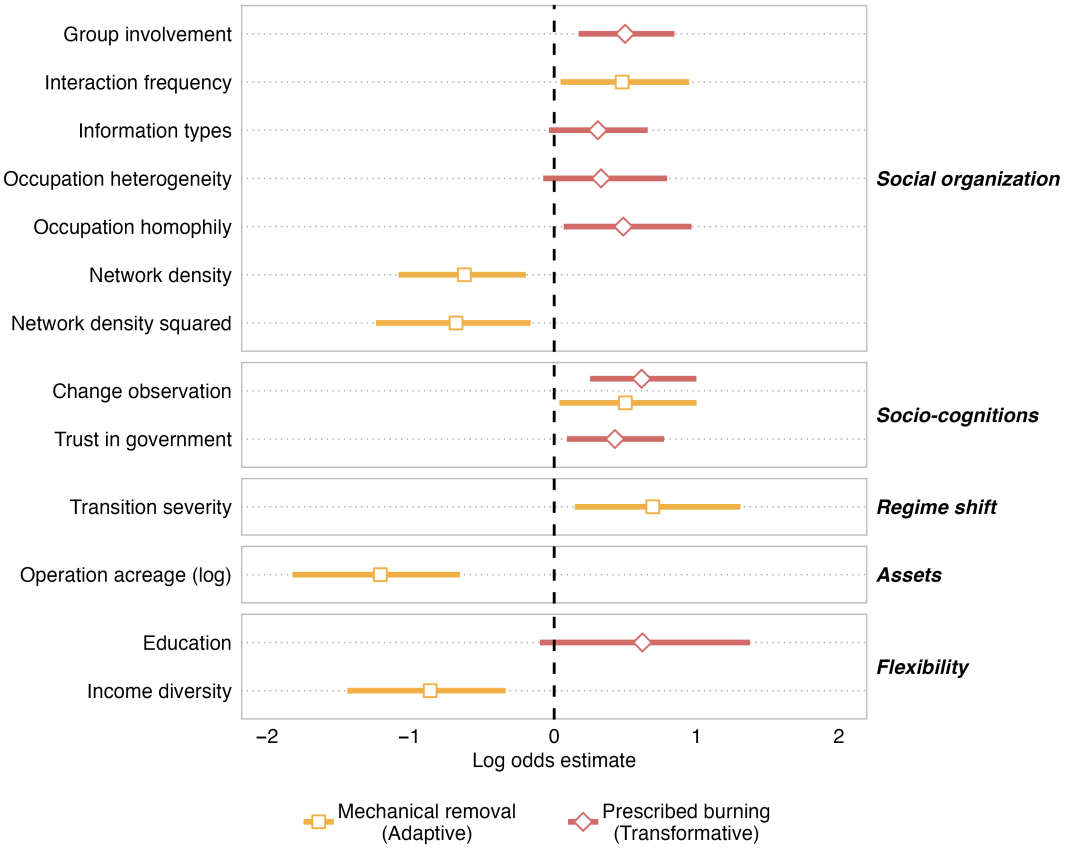

FIGURE 6 Log odds estimates for parameters in each final model (based on Akaike's information criterion) predicting mechanical removal and prescribed burning. The square and diamond symbols denote the point estimates and the bars denote the 95% confidence interval.

types; log odds = 0.31, CI = [−0.04, 0.66]) and diversity among contacts' occupations (i.e. occupation heterogeneity; log odds = 0.33, CI = [−0.08, 0.79]) were positively related to prescribed burning. Whereas, transition severity, our measure of regime shifts, was not in the final prescribed burning model indicating that it did not add further predictive power to the model given the other variables present.

3.2.2 | Hypothesis 2—Regime shifts will be more predictive of adaptive behaviour than social networks

Transition severity was equally or more predictive than social network variables in our mechanical removal model with among the largest effect sizes of the social network and regime shift variables, partially supporting our second hypothesis (Figure 6; Table S3). In particular, transition severity (log odds = 0.69, CI = [0.15, 1.31]) was significantly and positively related to mechanical removal while of the social network variables, network density and interaction frequency were related to mechanical removal.

3.2.3 | Hypothesis 3—Socio-cognitions will be predictive of both management behaviours

We also found evidence to support our third hypothesis that socio-cognitions would be predictive of both behaviours (Figure 6; Table S3). In particular, self-reported observation of regime shifts (i.e. change observation; log odds = 0.61, CI = [0.25, 1]) and trust in government (log odds = 0.43, CI = [0.09, 0.77]) were significantly ($p < 0.05$) and positively related to prescribed burning, and change observation (log odds = 0.5, CI = [0.04, 1]) was significantly and positively related to mechanical removal.

3.2.4 | Hypotheses 4–6—Social networks and management behaviours

We found no evidence that producers with large networks would be more likely to engage in prescribed burning and some evidence that those with heterogenous networks would be more likely to engage in prescribed burning. Producers with homophilous networks were significantly more likely to engage in prescribed burning. Contrary to our hypotheses, we found that strong ties and moderate densities were not related to prescribed burning but were related to mechanical removal. In particular, interaction frequency with contacts (log odds = 0.48, CI = [0.04, 0.95]) was significantly and positively related to mechanical removal, while network density (log odds = −0.63, CI = [−1.09, −0.2]) and network density squared (log odds = −0.69, CI = [−1.25, −0.17]) were significantly and negatively related to mechanical removal. The presence of both linear and quadratic density terms for density indicates that the relationship between mechanical removal and density is non-linear, such that mechanical removal

is most likely at moderate densities and least likely at low and high densities.

3.2.5 | Hypotheses 7 and 8—Regime shift observations, transition severity, and management behaviours

We found strong evidence that producers who observe woody encroachment will be more likely to engage in management behaviours. We found that increasing transition severity was predictive of mechanical removal but, contrary to our hypothesis, not prescribed burning.

3.2.6 | Hypotheses 9–11—Social norms, risk, trust and management behaviours

We found no evidence to support our hypothesis that producers who perceive social norms to manage encroachment or risk from encroachment would be more likely engage in management behaviours. We found that producers with greater trust in government were more likely to engage in prescribed burning, but contrary to our hypothesis, not mechanical removal.

3.2.7 | Covariates

Education (log odds = 0.62, CI = [−0.1, 1.38]) was the only covariate in the final prescribed burning model. Covariates in the final mechanical removal model included operation acreage measured on a log-scale (log odds = −1.22, CI = [−1.84, −0.66]) and income diversity (log odds = −0.87, CI = [−1.45, −0.34]).

4 | DISCUSSION

Our results demonstrate that social dimensions of adaptive capacity—especially social organisation and socio-cognitions—predict adaptive and transformative behaviours to manage regime shifts in a threatened grassland SES. Social network and socio-cognitive variables were predictive of prescribed burning, a transformative behaviour that is the most effective at managing this regime shift at large spatial scales. Furthermore, while local transition severity was predictive of mechanical removal, it was not for prescribed burning, suggesting that social connections and cognitions, though often overlooked, are critically important for influencing transformative behaviour. These findings have direct implications for increasing producer responses and developing policy interventions to manage woody encroachment as well as for the study and management of SESs more broadly, highlighting that social networks and socio-cognitions play a critical role in adaptive and transformative responses to regime shifts. Leveraging an understanding of social networks and cognitions may help practitioners everywhere encourage sustainable behaviours through innovative policy initiatives and strategic outreach.

Social network processes may enable uptake of transformative behaviours that are effective at managing regime shifts across large spatial extents, such as prescribed burning (Garmestani et al., 2020). We hypothesised that actors with access to different sources of information through heterogenous networks would be more likely to have the knowledge and resources to engage in such a technique. We also hypothesised that actors with social support from their homophilous networks would have enough collective buy-in to safely manage fire across a landscape that spans multiple owners. Our evidence supports both hypotheses. Although seemingly contradictory, heterogeneity and homophily measure related, but different concepts that demonstrated little to no overlap between the study's respondents. Actors with heterogeneous networks tended to have large networks ($r = 0.29$ for heterogeneity and network size) and greater access to non-redundant information ($r = 0.37$ for heterogeneity and non-redundant information access) suggesting that these producers access diverse knowledge and resources through their network (André et al., 2017; Sandström & Carlsson, 2008). On the other hand, actors with homophilous networks tended to have a moderate number of contacts ($r = -0.07$ for homophily and network size) with whom they interacted frequently ($r = 0.3$ for homophily and interaction frequency) and received multiple types of information from each ($r = 0.18$ homophily and average information types/alter respectively), suggesting they have access to social support from their close knit communities (Barnes et al., 2020; McPherson et al., 2001; Newig et al., 2010). Thus, the ability to overcome fire exclusion paradigms and engage in coordinated collective action through formal or informal management groups is likely occurring through these two different network mechanisms that influence two different groups of actors—providing more reach for conservation efforts if both levers are pulled.

Even when individuals observe regime shifts, social connections and cognitions may play a larger role in influencing transformative behaviour than actual ecological conditions. For example, social networks, trust, and change observation were strongly associated with transformative behaviour, but actual transition severity on the landscape was not. Though prescribed burning is often implemented before grasslands have fully transitioned to woodlands or after trees have been thinned mechanically (Figure 2), our transition severity variable captured the intensity of spatial boundaries between grasses and trees, not tree cover, and so should have been less sensitive to the order of management operations. Thus, this result suggests low social support and information access may act as significant behavioural constraints for individuals seeking to implement transformative behaviours, even when regime shifts are locally severe. Based on pervasive perceptions of fire risk and the significant litigious and bureaucratic hurdles in place around prescribed burning (Weir et al., 2016), these constraints seem likely.

Adaptive behaviours, in contrast to transformative, may peak with individuals who interact more frequently with their contacts, have moderately dense social networks, and experience and observe local ecological change. Frequency of interaction may indicate a lack of isolation from the surrounding community and more access to social information (Reagans & McEvily, 2003; Uzzi, 1999; Uzzi & Lancaster, 2003). That adaptive behaviours peak at moderate densities is consistent with social network research in organisations—very low densities impede information access and high densities suppress behaviours that are inconsistent with others'. An optimised network would have some combination of ties that provide access to novel information and social support (Oh et al., 2004; Uzzi, 1999). Furthermore, network structure affects knowledge transfer; tacit or noncodified knowledge is developed through experience and is difficult to describe to others, thus it usually requires dense networks for transfer, whereas transfer of novel information happens more often in open networks (Hansen, 1999). Given that mechanically removing trees is fairly straightforward, it seems reasonable that this type of behaviour would transfer readily through moderately dense networks. Different from prescribed burning, mechanical removal was more likely for producers who experienced severe transitions and observed local woody encroachment. Indeed, mechanical removal is one of the most widely used conservation incentives to manage woody encroachment by the USDA Natural Resource Conservation Service (NRCS; Scholtz et al., 2021; Roberts et al., 2018). Even so, mechanical removal was less likely among producers with large operations or more diverse income streams, which may be due to the time constraints of individual producers (especially those with off-ranch jobs), a lack of workforce support and contractors on private lands, and financial challenges associated with the escalating costs of increasing woody plant infestations (Scholtz et al., 2021; Twidwell et al., 2013, 2021). For example, costs to remove juniper range from dollars to thousands of dollars ($US) per hectare depending on the stage of encroachment. Cash flow is generally lacking for this type of investment for producers with severe encroachment on larger operations who are not eligible for cost-share programs administered by the NRCS if their Adjusted Gross Income is greater than $900,000 (USDA Farm Service Agency, 2024).

Social factors may constrain individual behaviour more than general knowledge of an issue or understanding of risk. In particular, even though most individuals perceived high risks from regime shifts, these risk perceptions were not predictive of adaptive or transformative behaviour, suggesting that a deficit of risk information is not the issue (Heberlein, 2012). Instead, it is more likely that low experience and low collective support for controlling junipers at scale is limiting regime shift management. For example, not having the skills and support to navigate approvals and implement unpopular and onerous, but effective, techniques (Weir et al., 2016) are likely limiting behaviour more than underestimation of risk. This result suggests that "information out" campaigns may have been effective at improving individuals' understanding of risk, but not changing their behaviour. Thus, outreach efforts that provide social support and target socio-cognitive constraints may be more effective at changing behaviour (Heberlein, 2012), particularly for transformative actions like prescribed burning (Weir et al., 2016).

Woody encroachment, an SES regime shift, is a large scale threat to the American Great Plains biome (Uden et al., 2019) that requires a matching scale of social response (Weir et al., 2016). Our findings are informative for those seeking to encourage producers to manage woody encroachment on their operations or to encourage collective action among producers on the larger landscape. There is a considerable, ongoing effort by extension professionals, non-profits, researchers, and agencies to support producers managing this regime shift (Twidwell et al., 2013, 2021; Weir et al., 2016). Some of these efforts target the constraints on individual behaviour that we identified here, including providing physical human labour, information and resources. Yet our research also shows that implementing prescribed burning is a collective action problem that requires social support at levels beyond the individual (Twidwell et al., 2013; Weir et al., 2016). In particular, we demonstrate that networks and rangeland management groups were predictive of prescribed burning. Supporting groups like prescribed burn associations with further capacity and building extensive prescribed burn networks through higher level policy initiatives may be effective. Given that trust in government was also predictive of prescribed burning, increasing on the ground presence and funding or providing more consistent messaging across agencies and levels (Stern & Coleman, 2015) may be effective. For example, rethinking cost-share programs for windbreak establishment to reduce the risk of encroachment in grasslands and updating guidelines to manage encroachment from existing windbreaks (Nebraska Association of Resources Districts, 2021) would be more consistent with management guidelines released by the USDA to manage encroachment risk (Natural Resources Conservation Service, 2021). While it is possible this change may improve trust in government, without question it would reduce invasive propagule sources in grasslands.

5 | LIMITATIONS AND FUTURE RESEARCH OPPORTUNITIES

There are a few caveats to our research that require consideration. Due to budgetary limitations, we sampled a cross-section of Nebraska that is representative of the woody encroachment gradient. Though not representative of all producers in Nebraska, the patterns in our data illustrate relationships between social networks/cognitions and behaviour among ranchers who responded to the National Agricultural Statistics Service's (NASS's) survey with 20 to 30,000 acres in pasture/rangeland and have experienced a wide gradient of woody encroachment. After vetting our results with several producers and conservation professionals across the state, our findings are consistent with their experiences, at least anecdotally, and suggest that additional inquiry is warranted.

This research illuminates further questions for exploration that may help inform higher level policy to manage regime shifts at scale. For example, it may be helpful to understand how regime shift scales

affect individuals to use transformative actions and whether social networks across broader landscapes, ecoregions, and biomes play a role in disseminating information and influencing behaviour. While we did not find support for our hypothesis that transformative behaviours would peak at moderate ego network densities, considering both ego and global network effects may reveal different patterns. For example, it may be that transformative behaviour peaks at some moderate level of connectedness among community clusters, much like Uzzi and Spiro's (2005) work on small worlds. If spatially dispersed connections among communities do play a role, participatory processes that connect individuals with diverse occupations and regime shift experiences across the biome may facilitate mutual understanding and social learning (Teodoro et al., 2021). Particularly if boundary spanners are also opinion leaders within their own communities (Matous & Wang, 2019), influencing proactive behaviour before individuals experience shifts may be possible. Performing a whole network analysis on collectives that are effectively managing regime shifts at scale, paired with qualitative analyses such as interviews and document review, may reveal barriers and opportunities for creative policy makers to implement specific interventions. Using big data and microtargeting techniques may help identify concentrated areas of producers who are likely to use prescribed burning techniques based on their data profiles and social connections (Metcalf et al., 2019).

6 | CONCLUSION

Given the rapid global change and sustainability issues we continue to face, understanding how people can create or maintain the SESs in which they want to live is essential (Higuera et al., 2019). This research provides quantitative evidence of how social networks enable adaptive and transformative responses to broad scale regime shifts. We used a novel ego network approach, compatible with standard survey design and statistical procedures, which may be illustrative for other researchers interested in understanding how social relations influence individual behaviours within a population. Furthermore, we demonstrated how regime shifts mobilise adaptive but not transformative behaviour. This finding points to the important, but rarely quantified interaction between social and ecological variables, suggesting that social constraints can substantially limit transformative behaviour even when ecological manifestations of a regime shift are obvious and the consequences of inaction are well known.

AUTHOR CONTRIBUTIONS

Holly K. Nesbitt, Alexander L. Metcalf, Theresa M. Floyd, Daniel R. Uden, Brian C. Chaffin, Sabrina Gulab, Simanti Banerjee, Sechindra Vallury, Dillon T. Fogarty, Dirac Twidwell and Craig R. Allen conceived the ideas and designed methodology; Holly K. Nesbitt, Sabrina Gulab, Daniel R. Uden and Samantha L. Hamlin collected the data; Holly K. Nesbitt, Alexander L. Metcalf, Theresa M. Floyd, Daniel R. Uden and Elizabeth Covelli Metcalf analysed the data; Holly K. Nesbitt led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

Data are available at https://doi.org/10.5281/zenodo.11625619.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. Methods.

Table S1. Variables included in models and their scale, question wording, mean and standard deviation (SD), Cronbach's alpha, and citation. Median (*) is shown for operation acreage.

Table S2. Fit and diagnostics for each model.

Table S3. Log odds estimates and 95% confidence intervals (CIs) for standardized parameters in each reduced model (based on Akaike's Information Criterion) predicting mechanical removal and prescribed burning.

Figure S1. Frequency of alter occupations (a) and demographic profile of our respondents (b–e).

Figure S2. Data distributions for the social organization variables in our models.

Figure S3. Data distributions for the socio-cognitive variables in our models.

Figure S4. Data distributions for the transition severity, agency, assets, and flexibility, and learning variables in our models.

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